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WHISTLER PRECURSORS: A POSSIBLE CATALYTIC ROLE OF POWER LINE RADIATION

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Abstract. Whistler precursors are discrete rising tone emissions that precede two-hop whistlers, starting shortly (0.1-0.3 s) after the one-hop delay. New data from Siple Station, Antarctica, and Roberval, Quebec, are introduced suggesting that precursors start at power line harmonics (PLH) from the Canadian electricl power system. To explain precursor triggering, a new two-stage mechanism is proposed in which the upgoing whistler interacts through longitudinal resonance with energetic electrons, thus modifying their distribution function. These electrons then interact through cyclotron resonance with the backward traveling PLH waves, causing these waves to grow to the level where they can trigger precursors. The PLH thus acts as a kind of catalyst in converting a particle perturbation to a backward traveling wave. This explanation, if correct, opens up a new realm of study in which whistler mode waves can be used to create a temporary perturbation in the energetic particle distribution. Such control is needed to conduct experiments on the factors (anisotropy, flux) that affect wave-particle interactions in the magnetosphere.

1. Introduction

Two-hop whistlers received on the ground are sometimes preceded by precursors that consist of one or more discrete rising tone emissions. This precursor phenomenon has been discussed by a number of authors, including Helliwell [1965], Laaspere and Wang [1968], Molchanov and Chmyrev [1970], Dowden [1972], Reeve and Boswell [1976], and Reeve and Rycroft [1976].

Figure 1a shows an example of precursors recorded at a pair of conjugate stations, Roberval, Quebec, and Siple, Antarctica. The arrows mark the causative sferic that produced the whistler and its echoes. At Roberval a precursor in the form of a rising tone emission arrives before the two-hop whistler. The precursor also echoes back to Siple and is observed there at ~1412:08 UT. The travel time from Roberval to Siple indicates that the precursor was propagating in the same duct as the whistler component labeled A. Figure 1b shows a more complicated precursor consisting of five discrete emissions, which in turn appear to trigger new emissions as they echo back to Siple. These events will be discussed later in more detail.

It is generally accepted that precursors are triggered by the same lightning discharges that produce associated whistlers. However, the triggering mechanism remains unexplained because precursors exhibit several properties that are difficult to reconcile with accepted theories of emission generation. Other, more common types of discrete emissions triggered by whistlers or man-made signals are believed to involve cyclotron interactions between waves and energetic electrons near the equatorial plane. In this mechanism, however, both triggering and triggered signals must propagate in the same direction. This is clearly inconsistent with the fact that precursors are first observed in the hemisphere of the causative sferic and that the time delay is significantly less than the two-hop whistler delay.

Two basically different approaches have been taken to get around this difficulty. In the first approach the cyclotron interaction mechanism is still assumed, but the triggering signal is required to turn around somehow so that it reaches the interaction region with approximately one-half-hop delay and with the wave normal pointed toward the source hemisphere. Helliwell [1965] and Dowden [1972] suggested that 'hybrid whistlers' might provide the requisite triggering signal. (Hybrid whistlers are produced by radiation from lightning that first propagates to the conjugate hemisphere in the earth-ionosphere waveguide and then returns to the source hemisphere via magnetospheric paths [Helliwell, 1965].) Reeve and Rycroft [1976] recently suggested that the triggering signal originating from lightning propagates in a nonducted mode to the conjugate hemisphere, is magnetospherically reflected at the point of lower hybrid resonance (LHR), is deflected by the plasmapause, and then enters a whistler duct near the equatorial plane where it can trigger the precursor through cyclotron resonance. This mechanism requires a combination of several special conditions to get the triggering signal at the right place at the right time.

In the second approach the triggering signal is assumed to propagate in a usual ducted mode, but the resulting precursor propagates in the opposite direction, toward the hemisphere of the causative sferic. This requires a backward triggering mechanism that operates near the equatorial plane. Parametric decay has been suggested as a possible mechanism [Molchanov and Chmyrev, 1970; Reeve and Boswell, 1976].

All the theories that have been advanced thus far appear to have serious difficulties in explaining one or more aspects of the precursor phenomenon (see section 3). In this paper we present some observational results that strongly suggest a new approach. In this new approach, coherent waves in the magnetosphere originating from electrical power distribution systems [see Helliwell et al., 1975] play a critical role in the generation of precursors. We believe that precursors are only one aspect of a class of wave-particle interactions that may very well be responsible for a variety of other unexplained magnetospheric phenomena. Thus an understanding of precursors may lead to understanding of a number of other wave and particle phenomena in the magnetosphere.

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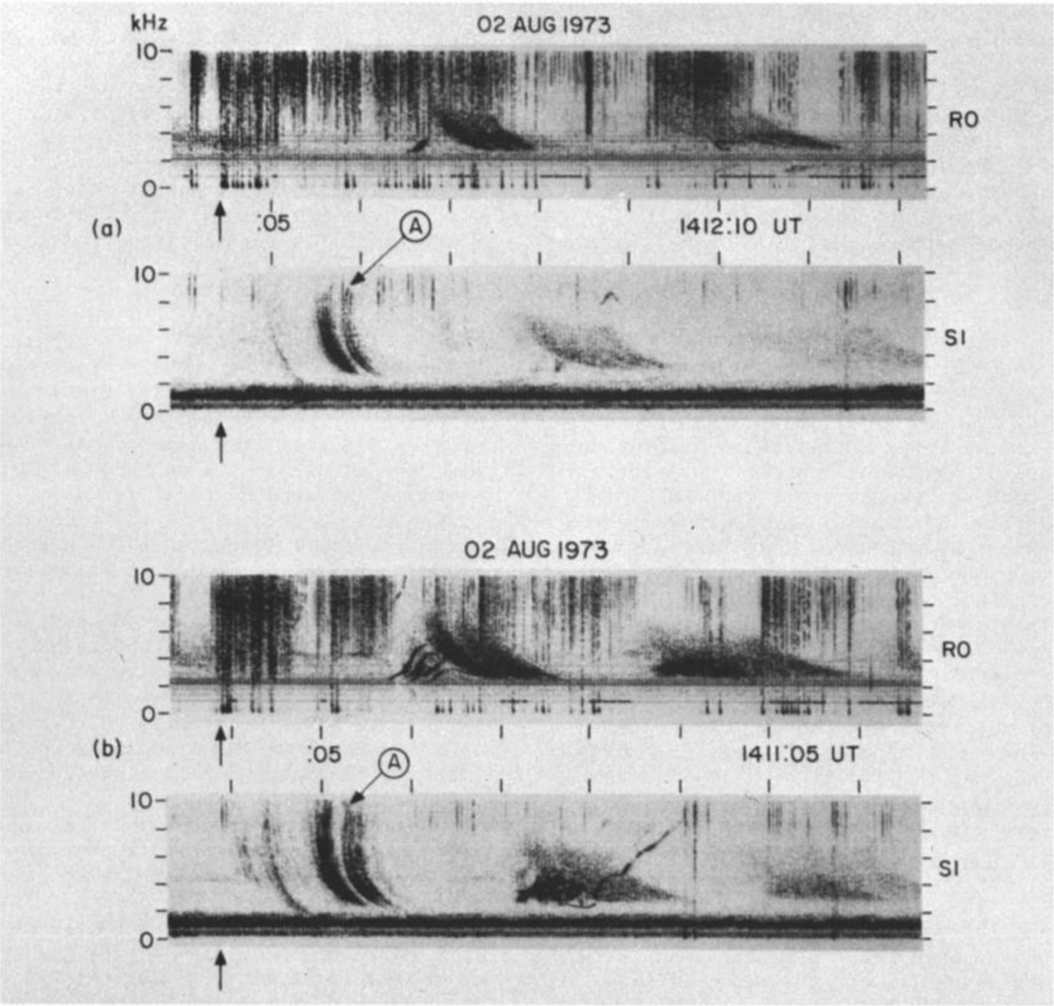

Fig. 1. Two examples of whistler precursors illustrated by simultaneous frequency-time spectrograms from Roberval, Quebec (RO), and Siple, Antarctica (SI). See text for details.

2. Observations

The present study is based on simultaneous VLF recordings made at a pair of conjugate stations, Siple, Antarctica, and Roberval, Quebec, near $L = 4$. There was a period of exceptionally good precursor activity on August 2, 1973. At the peak of the activity, at least 90 clearly identifiable precursors were observed during an 80-min period between 1335 and 1455 UT. All the examples discussed in this paper come from this 80-min period. The magnetic condition was moderately disturbed, with a 3-hour Kp index of 4+. During the preceding 24 hours the Kp index ranged from 1+ to 4.

The precursors observed during this period varied greatly in complexity, as is illustrated in Figure 1. The starting frequency of precursors ranged from ~2.2 to ~3.7 kHz. The time delay between the causative sferic and the triggering point as observed at Roberval was generally 0.1-0.3 s longer than the one-hop whistler delay along the ducted propagation path.

Path analysis. Many of the precursors observed at Roberval during the period of this study showed echoes at Siple. This permitted positive identification of their propagation path by comparing their travel times with those of discrete whistler components. Significantly, in all such cases the path was identified as one particular whistler duct that we labeled A in Figure 1. Even in those cases where a precursor consisted of two or more discrete emissions with different starting frequencies and times, it could be established that they were all triggered in duct A.

The results of path analysis can be summarized as follows. Of a total of 90 precursors observed, 28 showed clearly discernible discrete echoes. Of these 28, positive path identification was possible in 22 cases, including 11 cases of multicomponent precursors. In all 22 cases the path was identified as duct A.

In 6 cases the path could not be identified unambiguously because of mixed-path propagation, which allowed a signal originally propagating in one duct to echo back in two or more ducts. This was sometimes further complicated by closely spaced multiple emission elements within a precursor. Figure 1b shows an example. In all of the 6 ambiguous cases, however, the data were found to be consistent with the assumption that the precursors were triggered in duct A, although other possibilities could not be ruled out. Thus it appears that the generation of precursors was closely related to some special properties of duct A. But what are those properties?

The whistlers in Figure 1 are fairly typical of those observed during the period of this study. Duct A does not appear to produce stronger whistler traces compared with neighboring ducts. Nor is there any unusual spectral characteristic that distinguishes it from its neighbors.

Figure 2 shows a plot of equatorial electron density versus L, deduced from whistlers recorded near 1520 UT, when the plasmapause was clearly visible. No significant cross-L drifts or changes in electron density were evident during the entire period of interest. Apparently, there was nothing special about the location or electron density of duct A. As is shown in the following section, its special properties apparently were the result of wave activity due to power line radiation.

Power line radiation. Helliwell et al. [1975] showed that under certain conditions, radiation from power transmission lines on the ground can leak into the magnetosphere and produce strong wave-particle and wave-wave interactions. The power line harmonics (PLH) in a few kHz range may be greatly amplified in the magnetosphere and may stimulate emissions in much the same way VLF transmitter signals do [Helliwell and Katsufrakis, 1974] . Sometimes such power line induced activity completely dominates the VLF spectrum in the 1 to 10 kHz range [Park, 1976]. There is also strong evidence that even when the PLH is too weak to be detectable on standard spectrograms, it may still have profound influence on magnetospheric wave activity through wave-wave interactions. Such effects have been clearly demonstrated by controlled wave injection experiments using a VLF transmitter at Siple. In these experiments the transmitted pulses themselves were barely detectable in the conjugate hemisphere, but they strongly modified the frequency and amplitude characteristics of other much stronger emissions [Helliwell and Katsufrakis, 1974]. During the period of this study, strong line emissions that were observed at both Siple and Roberval showed the characteristics of power line induced emissions reported earlier by Helliwell et al. [1975] and Park [1976]. Sometimes their spectral form as well as their intensity changed significantly with time scales of the order of minutes. Figure 3 shows two different forms observed approximately 25 min apart.

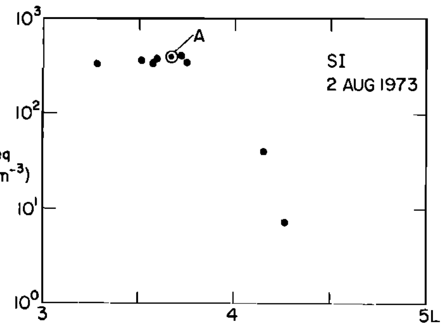

Fig. 2. Equatorial electron density versus L value near 1520 UT. Each data point represents a discrete whistler duct.

In Figure 3a, simultaneous Roberval and Siple records show line emissions near 4 kHz that appear alternately at the two conjugate stations. Some of the lines show considerable frequency broadening, and some trigger rising tone emissions. Both of these features are characteristic of artificially stimulated emissions [see, for example, Stiles and Helliwell, 1975]. The continuous lines below ~3 kHz seen at Roberval but not at Siple are locally produced induction lines, and their frequencies are odd multiples of the 60-Hz power frequency. In Figure 3b, several discrete line emissions between ~3.0 and 3.5 kHz are seen simultaneously at both stations, but unlike the first example there is no periodic modulation in their intensity. At Roberval, local induction lines are also seen below ~3 kHz as in the first example.

The properties of these line emissions, including conjugacy, whistler mode periodicity (in the case of Figure 3a), frequency broadening, and triggering of rising tone emissions, indicate that they are magnetospheric signals. We believe that these emissions were stimulated by radiation from the Canadian power distribution system in the manner discussed by Helliwell et al. [1975].

If line emissions show whistler mode periodicity as in Figure 3a, it is possible to identify their propagation path by comparing their period with whistler time delays. It is found that all power line induced emissions whose path could be identified during the period of this study propagated in duct A, the duct in which precursors were found to have been generated. We therefore suggest that power line radiation plays a critical role in the generation of whistler precursors. A possible mechanism of precursor generation involving power line radiation is discussed in the following section.

It is not unusual for power line effects to be confined to one duct when there are many closely spaced ducts that are capable of guiding whistlers from hemisphere to hemisphere [see Park, 1976]. This can be explained as follows. Since power line radiation entering the magnetosphere is very weak, it must be greatly amplified before it can produce any detectable effects. This usually requires several passages through the wave growth region near the equator. In support of this argument we note the fact that power line effects are observed only when strong whistler echoes or periodic emissions indicate good echoing conditions. Under these conditions, waves in one duct can frequently couple into neighboring ducts near the duct endpoints, thus resulting in mixed-path propagation, as was referred to earlier in connection with echoing precursors. When waves from different ducts are mixed in this way, the phase coherence is destroyed and growth is suppressed [Raghuram et al., 1977]. Therefore there is a tendency for mutual annihilation among echoing waves in neighboring ducts. If one duct has echoing properties slightly superior to those of its

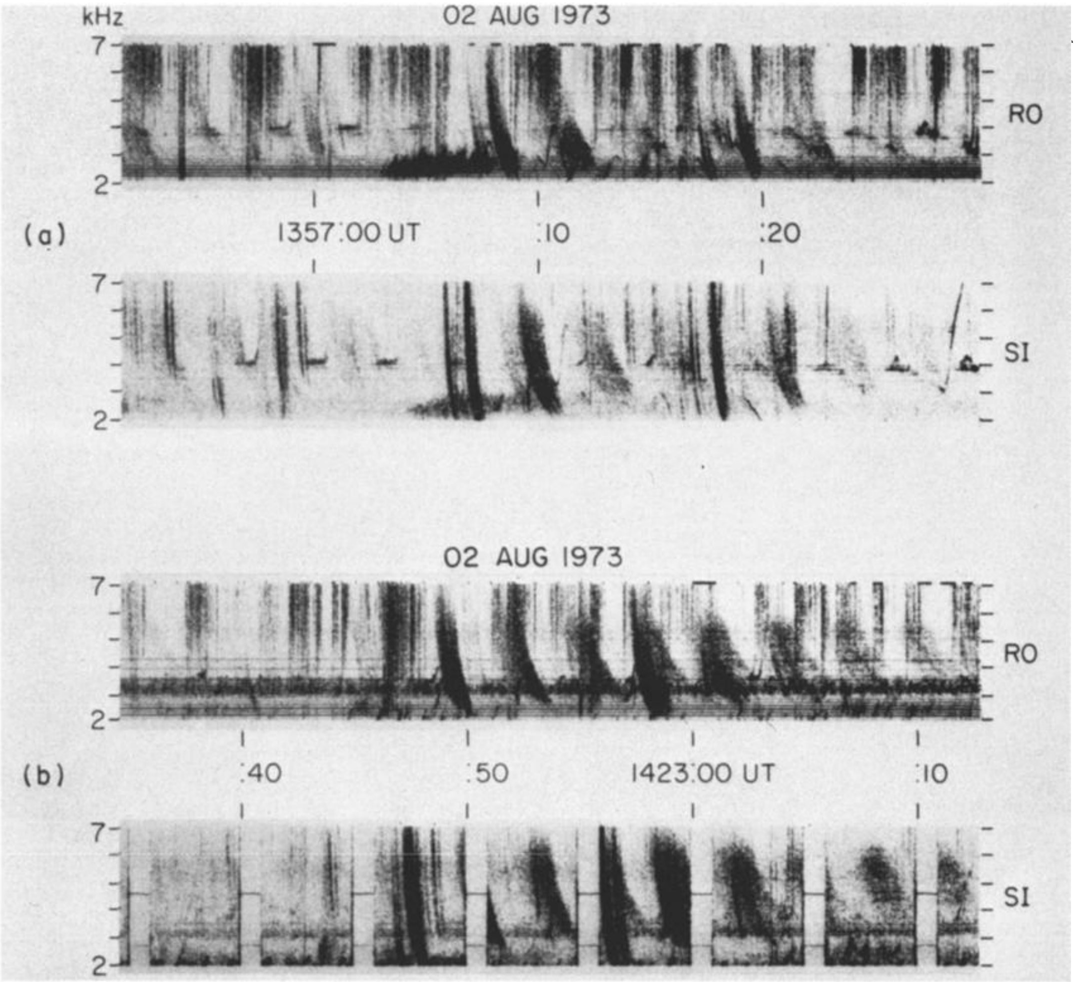

Fig. 3. Frequency-time spectrograms illustrating two examples of power line induced magnetospheric emissions recorded simultaneously at Roberval, Quebec (RO), and Siple, Antarctica (SI). The bottom panel shows data gaps every 5 s due to the operation of a VLF transmitter at Siple.

neighbors, this duct can emerge as the only active duct by suppressing growth in other ducts. As we shall see later, duct A indeed showed better echoing than its neighbors.

The triggering frequency of precursors. As was mentioned previously, the triggering frequency of precursors varied from ~2.2 to ~3.7 kHz. Near the triggering point the precursor amplitude grows rapidly in time as in the case of emissions stimulated by transmitter signals [Stiles and Helliwell, 1975]. In many cases, when the background noise level is low, it is possible to trace the precursors back to their origin to determine their starting frequencies. Figure 4 shows three examples. The precursors are apparently triggered at odd multiples of 60 Hz, conveniently marked by local induction lines at Roberval. The top spectrogram shows a precursor starting at the forty-first harmonic of the 60-Hz power frequency. In the middle record a precursor starts at the thirty-ninth harmonic and appears to be suddenly intensified at the forty-first harmonic. The bottom record shows four emissions starting at the thirty-seventh, forty-first, and forty-fifth harmonics of 60 Hz. This is presented as additional evidence linking power line radiation with precursors, although it is not possible to trace every precursor to its starting frequency.

Other phenomena associated with duct A. Whistler duct A provided a path for several other interesting wave-wave interactions that may be related to the precursor phenomenon. Figure 5 illustrates an example. The two top panels show simultaneous records from Roberval and Siple near 1352 UT. A lightning discharge in the northern hemisphere at $t = 0$ produced a train of whistler echoes. At Roberval the two-hop whistler is followed by a rising tone emission, which later appeared at Siple in a dispersed form at $t \simeq 5.5$ s. Based on its dispersion, we can identify duct A as the propagation path. The Roberval record is shown again at the bottom in an expanded frequency scale. When the two-hop echo of whistler trace A reaches the forty-fifth harmonic of 60 Hz, it suddenly intensifies that line, which in turn triggers a rising tone emission ~300 ms later. This is evidence that whistlers were interacting with power line radiation in duct A and caused it to trigger emissions. Note that prior to its interaction with the whistler the power line radiation is not de-

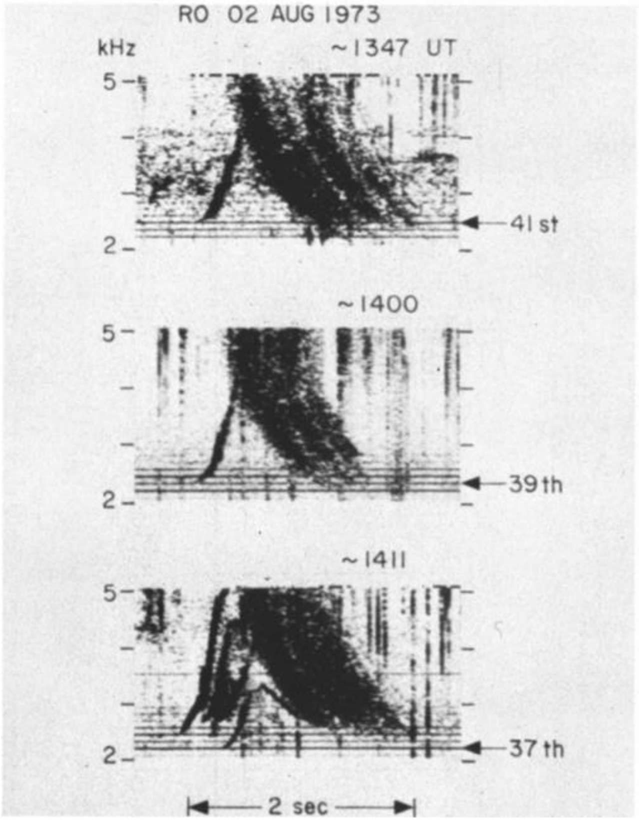

Fig. 4. Frequency-time spectrograms from Roberval, Quebec, illustrating the relationship between the precursor starting frequency and local induction lines at odd multiples of the 60-Hz power frequency. The harmonic numbers of the induction lines are shown at right.

tectable on the Siple record. This is consistent with the previous statement that a weak signal can entrain much stronger signals through wave-wave interactions. The interaction mechanism in this case, however, is believed to be the usual cyclotron resonance, since the two-hop whistler, the constant-tone emission, and the rising tone emission were all propagating in the same direction. As precursors seem to be triggered by one-hop whistlers, a backward triggering mechanism is required.

Figure 6 illustrates another interesting property of duct A. The top two panels show simultaneous spectral records from Siple and Roberval. The sferic marked with an arrow on the Roberval record excited a multicomponent whistler received at Siple. At least five discrete traces can be clearly seen at 1444:28 UT. The trace corresponding to duct A is so marked on the record. When this whistler echoed back to Roberval, the two-hop whistler labeled A_2 had only one trace, which then continued to echo back and forth, getting amplified and triggering emissions along the way. The successive echoes are labeled A_n, where n is the hop number. The echo period indicates that all the echoes and associated emission activity took place along duct A. This is evidence that duct A had superior echoing conditions compared with those of the neighboring ducts.

The two panels at the bottom of Figure 6 show echoes A_4 and A_{10} in expanded frequency and time scales. The emissions clearly show entrainment, or discontinuities in df/dt, which we believe are due to wave-wave interactions with power line radiation in duct A. In these cases it is difficult to measure the frequencies of interacting power line radiation because of the complex structure in the local induction lines. In the lower right panel, for example, note that the induction lines are not evenly spaced. This is believed to be due to two uncoupled power systems operating at slightly different frequencies. In the lower left panel, amplitude modulation of induction lines also suggests a small frequency offset between two power systems.

3. Mechanism

It is difficult to explain the observations described in the previous section in terms of any precursor generation mechanisms that have been advanced so far. (Recall, however, that all the observations reported here were made on one day. Thus we cannot rule out the possibility that the previously proposed mechanisms operate under different circumstances.)

One of the difficulties of the hybrid mechanism [*Helliwell*, 1965; *Dowden*, 1972] is the fact that no hybrid whistler was actually observed. Furthermore, one-hop whistler components that propagated through duct A were not any stronger than those that propagated through adjacent ducts. During the period of observation there was a lightning discharge in the southern hemisphere that produced a one-hop whistler at Roberval. Again, duct A did not produce a noticeably stronger whistler component compared with its neighbors. Thus it is difficult to argue that duct A had some special properties favorable for launching hybrid whistlers. Why then were precursors generated only in duct A?

The theory proposed by *Reeve and Rycroft* [1976] also has serious difficulties. As was pointed out previously, the starting frequency of precursors varied by factors of 1.5 or more, sometimes within a single multicomponent precursor. It is difficult to imagine that the very special propagation conditions required by this mechanism would be met over such wide frequency ranges and by only one out of several closely spaced ducts.

The parametric decay mechanism [*Reeve and Boswell*, 1976] cannot explain the generation of multicomponent precursors starting at different frequencies and times, all triggered by one whistler wave propagating in one duct. Furthermore, since this mechanism requires the wave normal angle to be close to the resonance cone, it us unlikely that such waves will penetrate the ionosphere and be received on the ground.

A new proposed mechanism. We saw in Figure 5 that a PLH could be intensified by a whistler and then later it could trigger an emission. Since we have found that precursors often originate at a PLH, it is natural to look for a mechanism in which the PLH again plays a key role in triggering.

Because of the difficulties with various wave triggering hypotheses, discussed earlier, let us

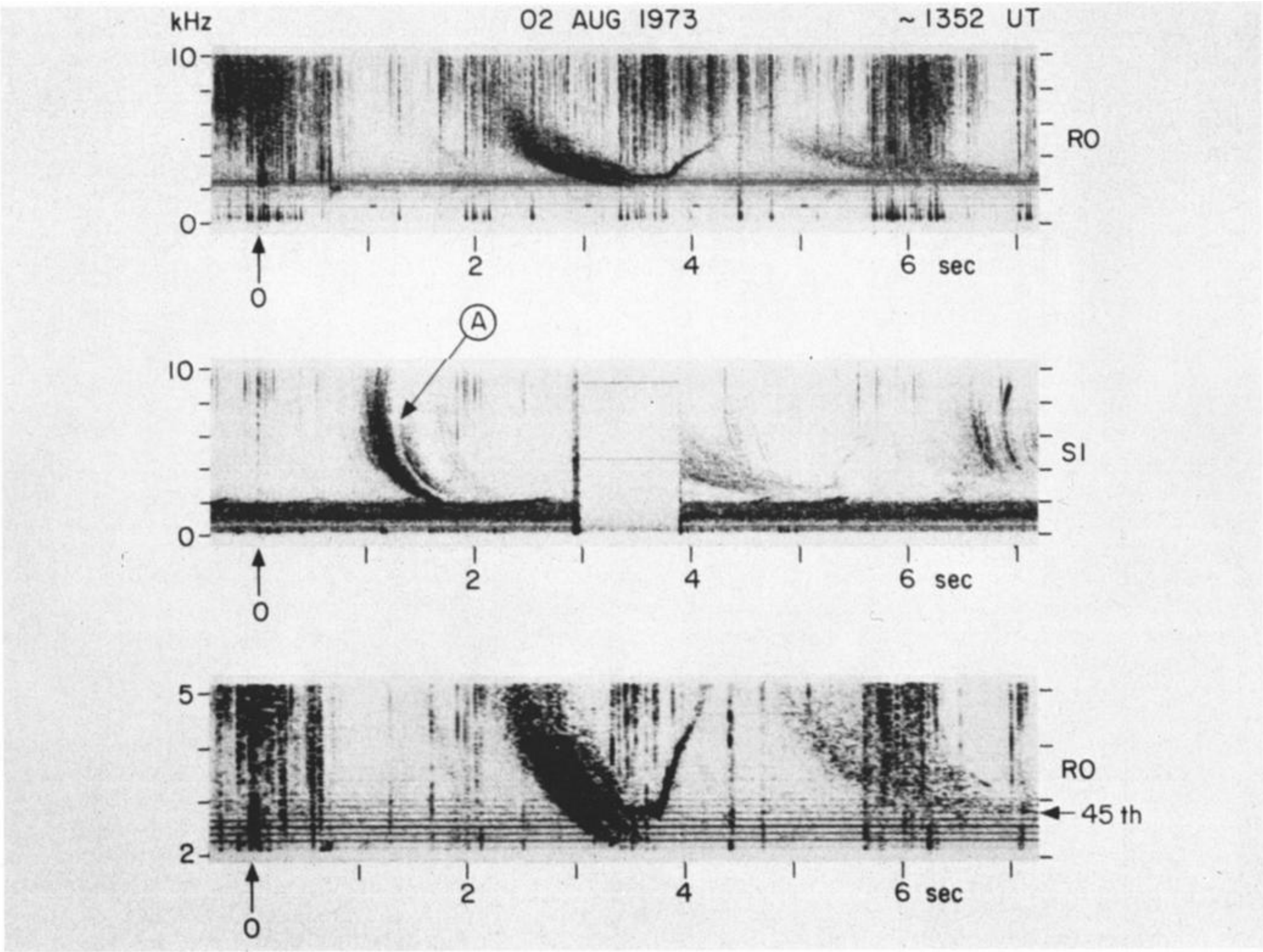

Fig. 5. The two upper panels are simultaneous frequency-time spectrograms from Roberval, Quebec (RO), and Siple, Antarctica (SI). The data gap between 3 and 4 s is caused by VLF transmissions from Siple. The Roberval record is reproduced in the bottom panel in an expanded frequency scale.

consider particle triggering. Suppose the magnetosphere is already close to the threshold of instability (see discussion below). If we could find a way temporarily to perturb the energetic electrons and cause the PLH to grow through cyclotron resonance, then we might trigger a rising emission. But such perturbation must be associated with the one-hop whistler component. Therefore the question becomes, How could a whistler perturb the distribution function of energetic electrons?

A possible answer can be found by considering the whistler duct to act like a giant linear accelerator or traveling wave tube. The ducted waves are assumed to have a significant longitudinal electric field $E_\parallel$ (see discussion below). This field will act to accelerate or decelerate electrons whose parallel velocity $v_\parallel$ approximately equals the parallel component of the wave phase velocity, v_p (longitudinal resonance). Now assume conditions are such that the spatial rate of change of the $v_\parallel$ of an initially resonant electron is slightly greater than the corresponding change in v_p of the wave in which the electron is temporarily trapped. In general this condition can be expected to obtain as electrons leave their mirror points and approach the equator. Then there will be a net perturbation in the number density of electrons close to $v_\parallel$ because all affected electrons are being slowed down rather than speeded up.

Consider a precursor generated in duct A. We assume that it is generated by cyclotron resonance near the equator. The resonance condition is

$$f(1 + \frac{v_\parallel}{v_p}) = f_H$$

where f is the wave frequency and f_H is the electron gyrofrequency. If we take 3 kHz for the precursor starting frequency and use the parameters of duct A deduced from whistlers ($L = 3.6$, equatorial electron density = 440 el cm^{-3}), we find that the equatorial parallel energy of resonant electrons is 8.4 keV. We now ask what the required conditions are for longitudinal resonance between these electrons and whistlers.

Consider an electron which at the equator has parallel energy $W_\parallel = 8.4$ keV and pitch angle α_{eq}. As this electron travels along an $L = 3.6$

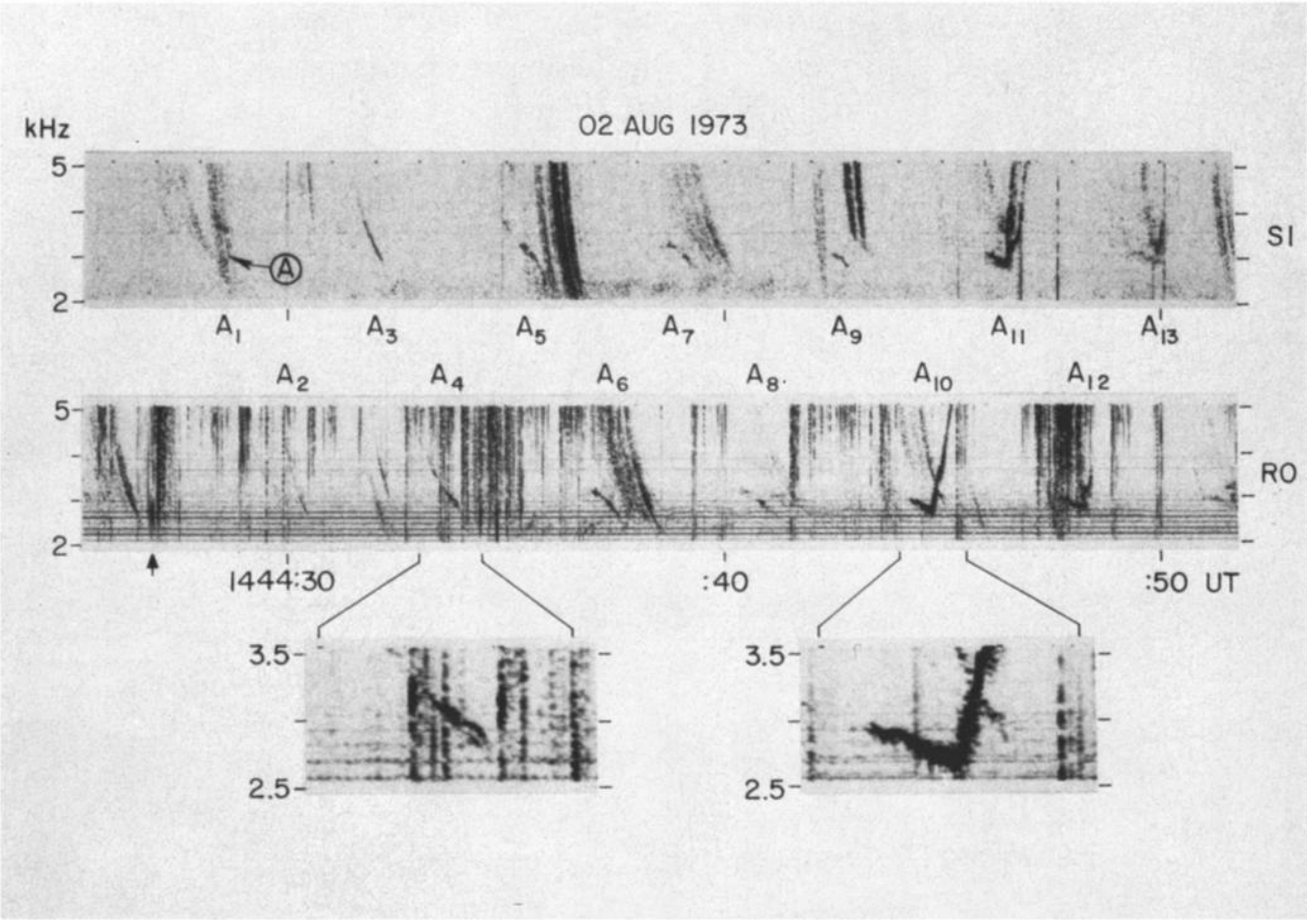

Fig. 6. The two upper panels are simultaneous frequency-time spectrograms from Siple, Antarctica (SI), and Roberval, Quebec (RO). Portions of the Roberval record are reproduced below in expanded frequency and time scales. See text for explanation.

field line to its mirror point, $W_\parallel$ will vary as shown in Figure 7 for different α_{eq}. For each $W_\parallel$ curve we can calculate longitudinally resonant wave frequencies by requiring that

$$v_\parallel = v_p = cf^{1/2}(f_H - f)^{1/2}/f_p$$

where f_p is the plasma frequency and c is the speed of light in free space. (Here for convenience we have taken the angle of the wave normal to be zero, although in practice it must be nonzero in order to provide a longitudinal component of electric field.) The resonance frequency is then given by

$$f = \frac{f_H \pm [f_H^2 - 4(v_\parallel f_p/c)^2]^{1/2}}{2}$$

The plus sign in the numerator gives $f > f_H/2$. At these frequencies, however, the waves are not trapped by enhancement duct and therefore are not expected to play an important role in the proposed mechanism. Using the minus sign and assuming a diffusive equilibrium plasma distribution along the duct, we obtain for longitudinal resonance the family of solid curves shown in Figure 7. The light dashed curve in the upper left corner indicates $f_H/2$. We can see that all whistler frequencies satisfy the longitudinal resonance condition somewhere between the particle mirror point and the equator.

At a given frequency a wave propagating toward the equator resonates with energetic electrons that have progressively smaller $W_\parallel$ but larger α_{eq}. If we consider particles with different α_{eq}, particles with $\alpha_{eq} = 10°$ can resonate with whistler waves ($f < f_H/2$) for ~8000 km (52°-34° latitude), while the corresponding distance for $\alpha_{eq} = 50°$ is only ~700 km (20°-19° latitude). Thus the proposed mechanism should be more effective for low pitch angle particles.

Precursor triggering is ascribed to a temporary perturbation, due to longitudinal resonance, in the cyclotron-resonant electrons. How long will the perturbation last? We can make a rough estimate as follows. Consider a whistler launched at t = 0. As it propagates toward the equator, it will resonate with different electrons according to the longitudinal resonance conditions depicted in Figure 7. The arrival time of perturbed electrons at the equator (wave propagation time to the resonance point plus particle transit time from there to the equator) depends on α_{eq} as well as the location of resonance. The earliest arrival time of 0.45 s is obtained for $\alpha_{eq} = 10°$, which is essentially the particle flight time from 50° latitude (we are assuming a whistler low-frequency cutoff at 2 kHz) to the equator. The

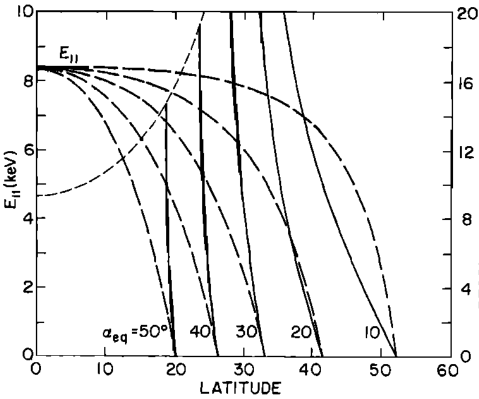

Fig. 7. The heavy dashed curves show variations in parallel electron energy ($W_{\parallel}$) as a function of latitude on an L = 3.6 field line for different equatorial pitch angles. The solid curves show corresponding variations in wave frequency for longitudinal resonance with the electrons. The light dashed curve at upper left shows variations in one-half electron gyrofrequency.

wave propagation time from the ground to 50° latitude is negligible. For α_{eq} = 50° we obtain an arrival time of ~0.7 s (0.5 s for wave propagation and ~0.2 s for particle transit). Thus the whistler-induced particle perturbation, as observed at the equator, would last for ~0.25 s. Since typical temporal growth times for coherent signals (through cyclotron resonance) range from 0.1 to 1 s [Helliwell and Katsufrakis, 1974], it appears that our estimated duration of particle perturbation may be long enough to carry the intensity of the PLH wave above the triggering level.

Next, we consider the arrival time of precursors at Roberval. At an average precursor starting frequency of 3 kHz, the observed arrival time is ~1.9 s. On the other hand, echoing precursors show that the one-hop travel time at this frequency is ~1.7 s. If we assume that precursors are triggered near the end of perturbed electron streams, we can find the location of triggering that is consistent with the timing of events discussed above. Thus we place the triggering point at ~11°S geomagnetic latitude, or ~5000 km off the equator. The tail end of a perturbed electron stream reaches this point at t = 0.75 s and triggers a northward propagating precursor which arrives at Roberval at t = 1.9 s. We note that the triggering point is on the upstream side of the equator, a necessary condition for triggering rising tone emissions [Helliwell, 1967]. The precursor arrival time quoted above refers to the first clear rising tone on Roberval records. Since it is possible for a precursor to be initially entrained for some time by the triggering PLH, our estimate of 5000 km from the equator to the triggering point should be regarded as an upper limit.

The proposed mechanism depends on the existence of significant $E_{\parallel}$ of the whistler wave. Although $E_{\parallel}$ = 0 for strictly longitudinal propagation, we note that the waves trapped in a duct may have wave normal angles as large as ~30° with respect to the geomagnetic field. Thus it is possible for ducted whistlers to have significant $E_{\parallel}$. The magnitude of $E_{\parallel}$ in terms of total wave power depends not only on the wave normal angle but also on the normalized wave frequency (f/f_H) [Budden, 1961]. We will not attempt to calculate $E_{\parallel}$ in this paper.

We have given only a qualitative description of the mechanism. In order to properly test this mechanism quantitatively, we need to calculate perturbations in electron fluxes as a function of time and position as a whistler wave packet propagates toward the equator. The results of detailed calculations will be reported at a later date. Another important problem is to determine what electron distribution function is required to initiate an emission. Although we do not yet know the conditions for instability, we argue that the system may very well be close to the threshold of triggering, requiring only a small perturbation to become unstable. We note that emissions are often triggered by very weak signals and that the triggering behavior changes rapidly (time scales of 1 min or less) even during magnetically quiet periods [Helliwell and Katsufrakis, 1974]. These observations suggest that indeed the magnetosphere is often close to the threshold of instability. Since the threshold for the triggered instability is much lower than that for the spontaneous instability, the presence of even a very weak PLH is crucial in initiating emissions. We propose that this is how the PLH plays a catalytic role in the generation of precursors.

4. Conclusions

To summarize, we propose a new two-stage mechanism for the production of precursors. A whistler induces a temporary perturbation in the costreaming energetic electron population through longitudinal resonance. As this perturbation crosses the equator, it interacts with oppositely traveling power line radiation through cyclotron resonance, causing these lines temporarily to increase their intensity. With sufficient amplification one or more of these lines trigger the precursor, a rising emission that travels down the field line, arriving at the ground slightly after the original one-hop whistler arrives at the conjugate point.

Confirmation of our proposed mechanism could lead to a new interpretation of other phenomena. For example, the periodic enhancement of NAA transmitter signals at the one-hop whistler period [Bell and Helliwell, 1971] might be explained by this mechanism. Our mechanism implies the possibility of wave growth through longitudinal resonance at large distances from the equator. Thus we might be forced to consider this new mechanism as well as transverse (cyclotron) resonance in the study of the growth of discrete VLF waves in the magnetosphere. An important feature of our mechanism is that the input wave that produces particle bunching need not be at the triggering frequency of the resulting emission. The proposed mechanism can be tested by sending appropriate pulses from Siple Station at times of PLH activity.

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References

Bell, T. F., and R. A. Helliwell, Pulsation phenomena observed in long-duration VLF whistler mode signals, J. Geophys. Res., 76, 8414, 1971.

Budden, K. G., Radio Waves in the Ionosphere, p. 53, Cambridge University Press, New York, 1961.

Dowden, R. L., Trigger delay in whistler precursors, J. Geophys. Res., 77, 695, 1972.

Helliwell, R. A., Whistlers and Related Ionospheric Phenomena, Stanford University Press, Stanford, Calif., 1965.

Helliwell, R. A., A theory of discrete VLF emissions from the magnetosphere, J. Geophys. Res., 72, 4773, 1967.

Helliwell, R. A., and J. P. Katsufrakis, VLF wave injection into the magnetosphere from Siple Station, Antarctica, J. Geophys. Res., 79, 2511, 1974.

Helliwell, R. A., J. P. Katsufrakis, T. F. Bell, and R. Raghuram, VLF line radiation in the earth's magnetosphere and its association with power system radiation, J. Geophys. Res., 80, 4249, 1975.

Laaspere, T., and C. Y. Wang, Whistler precursors, Radio Sci., 3, 213, 1968.

Molchanov, O. A., and V. M. Chmyrev, Possible generation mechanism of the precursors of whistlers, Geomagn. Aeron., 10, 816, 1970.

Park, C. G., The role of manmade VLF signals and noise in wave-particle interactions in the magnetosphere, in Physics of Solar Planetary Environments, Vol. 2, edited by D. J. Williams, p. 772, AGU, Washington, D. C., 1976.

Raghuram, R., T. F. Bell, R. A. Helliwell, and J. P. Katsufrakis, Echo-induced suppression of coherent VLF transmitter signals in the magnetosphere, J. Geophys. Res., 82, in press, 1977.

Reeve, C. D., and R. W. Boswell, Parametric decay of whistlers--A possible source of precursors, Geophys. Res. Lett., 3, 405, 1976.

Reeve, C. D., and M. J. Rycroft, A mechanism for precursors to whistlers, J. Geophys. Res., 81, 5900, 1976.

Stiles, G. S., and R. A. Helliwell, Frequency-time behavior of artificially stimulated VLF emissions, J. Geophys. Res., 80, 608, 1975.

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